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ORIGINAL ARTICLE

Opportunities for an African greenhouse gas observation system

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Abstract

Global population projections foresee the biggest increase to occur in Africa with most of the available uncultivated land to ensure food security remaining on the continent. Simultaneously, greenhouse gas emissions are expected to rise due to ongoing land use change, industrialisation, and transport amongst other reasons with Africa becoming a major emitter of greenhouse gases globally. However, distinct knowledge on greenhouse gas emissions sources and sinks as well as their variability remains largely unknown caused by its vast size and diversity and an according lack of observations across the continent. Thus, an environmental research infrastructure—as being setup in other regions—is more needed than ever. Here, we present the results of a design study that developed a blueprint for establishing such an environmental research infrastructure in Africa. The blueprint comprises an inventory of already existing observations, the spatial disaggregation of locations that will enable to reduce the uncertainty in climate forcing's in Africa and globally as well as an overall estimated cost for such an endeavour of about 550 M€ over the next 30 years. We further highlight the importance of the development of an e-infrastructure, the necessity for capacity development and the inclusion of all stakeholders to ensure African ownership.

Keywords Climate · Carbon dioxide · Methane · Nitrous oxide · Environmental research infrastructure

Introduction

The greatest increase in global population growth in the twenty-first century is projected to occur in Africa (FAO 2017), where much of the available uncultivated land required to meet global twenty-first century food demand is located (Ramankutty et al. 2018). Land use change in Africa is proceeding at an unprecedented rate, through agricultural expansion and urbanisation, leading to increased greenhouse gas (GHG) emissions, and it is expected that emissions from industrialisation, transport and power generation will follow suit (Liousse et al. 2014). For all these reasons, Africa can be expected to go from a footnote (~4%) to the global anthropogenic GHG emission inventories, to a major emitter (20%) over the next three decades. At the same time, the continent is already strongly affected by climate change and its vulnerability to extreme weather and climate conditions may increase during its further development.

At present, the infrastructure for quantifying the GHG sources and sinks in Africa is inadequate, due to the diversity of land cover, climate, management intensity and investment in capacity development, making the continent one of the weakest links in the global observation system (Ballantyne et al. 2015). More broadly, an integrated environmental research infrastructure (RI) in Africa is essential to achieve sustainable development and to guide the necessary investments. The need for such an infrastructure has been apparent for many years (see the commentary by Mbow (2014) on Valentini et al. (2014): "*Other future directions of research should include the creation of an inventory of databases of information from* in situ *studies, as part of a collaborative framework to improve the availability of low-cost greenhouse gas data*.").

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Such coordinated RIs are emerging worldwide (Franz et al. 2018; Steinhoff et al. 2019) and are helping to harmonise measurement and data-acquisition methods which then improves the consistency of the collected data (Chabbi and Loescher 2017). New generations of satellites, new automated measurement technologies and sophisticated modelling capabilities provide the opportunity to substantially improve greenhouse gas budgeting for Africa at both continental and national scale (Janardanan et al. 2020). Kulmala (2018) proposed that a minimum of 30 stations be built in Africa, comprising at least one in each key ecosystem and suggested that the best sites should be identified in collaboration with local organisations and scientists. Yet, a detailed assessment on available data and the requirements for establishing an environmental RI in Africa remains missing. In 2016, an EU-funded project entitled Supporting EU-African Cooperation on Research Infrastructures for Food Security and Greenhouse Gas Observations (SEACRIFOG) took up the challenge of designing such a system for the African continent and the results of this project are presented here.

Ecosystems of high importance to the global climate system, such as the Amazon basin or eastern-boundary ocean upwelling systems off North- and South America are much better monitored and understood than comparable areas in Africa (Chavez and Messié 2009; Davidson et al. 2012). Africa has unique natural attributes that are globally important in relation to the dynamics of the Earth system such as (1) wildfire emissions from the savannas of Africa constitute a large fraction of the global total (Lehsten et al. 2009; Archibald 2016), (2) dust emissions from the Sahara desert affect not only distant locations in Europe and the Americas (Knippertz and Knippertz 2017; Kok et al. 2018) but also fuel primary production in the Eastern Tropical North Atlantic through release of limiting macro and micro nutrients (Baker et al. 2013), (3) methane (CH_4) emissions from large wetlands on the Nile were previously not reported (Lunt et al. 2019), (4) nitrous oxide (N_2O) emissions from the Congo basin have for the first time been evidenced by measurements and satellite observations (Borges et al. 2015; Upstill-Goddard et al. 2017), (5) previously unknown hotspots of N_2O emissions related to agricultural practices were revealed (Butterbach-Bahl et al. 2020), and (6) emission hotspots of methane and nitrous oxide in the Canary Current (Kock et al. 2008; Wittke et al. 2010) and Benguela Current upwelling systems were identified (Arévalo-Martínez et al. 2019; Morgan et al. 2019). Thus, there is substantial evidence for the growing importance of Africa in the global GHG budget. Yet, the infrastructure that allows accurate spatial attribution of GHG emissions as well as tracking changes in GHG exchange over time remains lacking.

The guiding principle of the SEACRIFOG project is the cost-effectiveness and knowledge benefits of taking an Africa-wide integrated approach, rather than 55 individual national approaches. All African countries have reporting obligations under the United Nations Framework Convention on Climate Change (UNFCCC), which will become more onerous over time and will require more empirical data. Simultaneously, observing the climate forcing from an integrated continental scale observational network would clearly benefit all countries and strengthen their common position within the UNFCCC. In addition to national governments, international organisations such as the United Nations Environment Programme (UNEP), the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO) and the World Meteorological Organization (WMO), international and regional development banks, and private foundations all have an interest in supporting the emergence of such an RI in Africa. Accurate climate-related observations are an essential contributor to the evidence-based guidance of green development pathways which will be required as the population of Africa increases in a climatically uncertain future (Intergovernmental Panel on Climate Change (IPCC) 2013; Niang et al. 2015).

The design approach taken by the SEACRIFOG consortium

The SEACRIFOG consortium investigated: (1) the availability of ongoing and historical observations relevant to quantifying the African GHG budget (López-Ballesteros et al. 2018; Beck et al. 2019); (2) feasible designs and associated costs for an integrated environmental research infrastructure, primarily targeted at GHG emission quantification, that meets the requirements of the African continent and the globe (as determined by the UNFCCC reporting requirements and the global 'essential variable lists' respectively); (3) investment in human capacity by training future researchers in environmental observations and building a network of researchers to drive an African RI and use its data scientifically, jointly with partners from across the globe; and (4) the establishment of a stakeholder dialogue platform to create awareness and ownership of RIs at national and continental levels. Emphasis was given to building from what already exists, and to the involvement of African institutions. A systems-based approach was adopted to ensure that the most important climate forcing's are covered in a rigorous and balanced way with a maximum level of standardisation, while permitting the system to expand and adapt in the future. The measurements are based on internationally agreed 'essential variables' (Beck et al. 2019), with a combination of top-down and bottom-up approaches to allow the system to commence immediately and then progressively reduce uncertainties over time, and built-in redundancy to provide robustness.

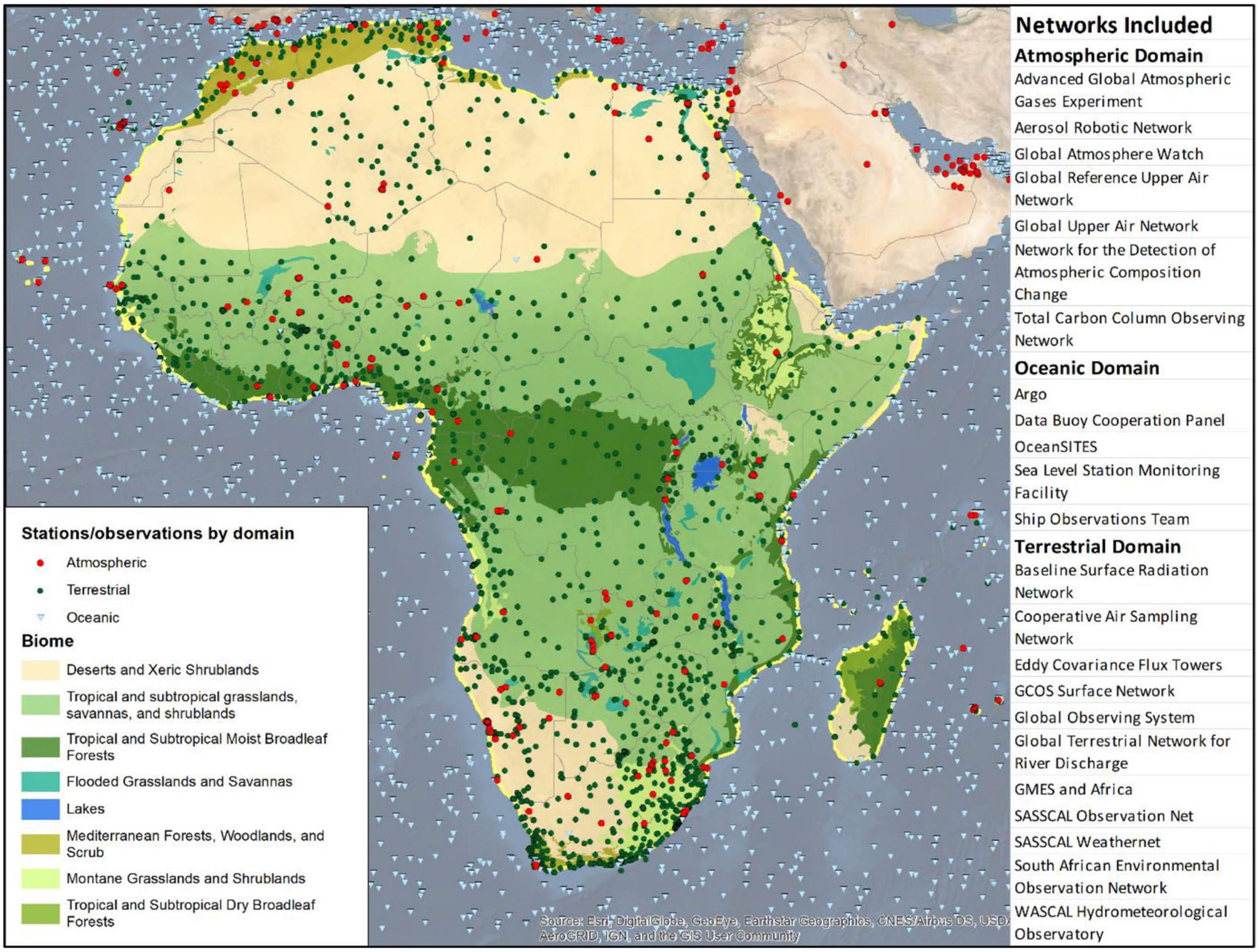

Fig. 1 Observation sites associated with selected networks as of 2018 (updated following López-Ballesteros et al. 2018). The spatial coverage as well as total numbers of oceanic sites may be misleading, as the majority of sites presented here (light blue dots) are based on the international Argo programme (Roemmich et al. 2019), a global network of autonomous profiling drifters. Here, all observations between 2000 and 2018 are shown. Typically, only vertical profiles of temperature and salinity in the upper 2000 m of the water column are obtained and these are not GHG observations

Current state of environmental observations in Africa

Compared to other continents, and in particular Europe, North America and Australia, existing environmental observations in and around Africa remain limited and piecemeal (López-Ballesteros et al. 2018). Nevertheless, the African continent is far from being an observational *terra incognita*. An inventory of in situ[1] observational locations associated with 25 research networks and initiatives revealed multiple locations of observations on and around the continent[2] as of 2018 (Fig. 1). This includes both operational and inactive sites, with the current operational status of most sites (84%) being unknown. An analysis of the observational coverage of the major natural and anthropogenic biomes (López-Ballesteros et al. 2018) showed that areas that are significant to the global climate system, such as the tropical rainforest in equatorial Africa are only sparsely covered. Station density increases with the degree of human disturbance, which results in few observations in less disturbed ecosystems. An integrated continental climate forcing observation system would build on the existing infrastructure while establishing new sites to systematically close coverage gaps. In general, the marine coastal and open-ocean ecosystem can be considered as highly undersampled compared to terrestrial ecosystems caused by their remoteness and the tremendous effort (infrastructure investments, manpower, shipping time requirements, costs) to operate and maintain offshore sites. At

[1] i.e. not taking into account air- and space-based observations.

[2] Between – 26 and 64° longitude and 28 and – 40° latitude.

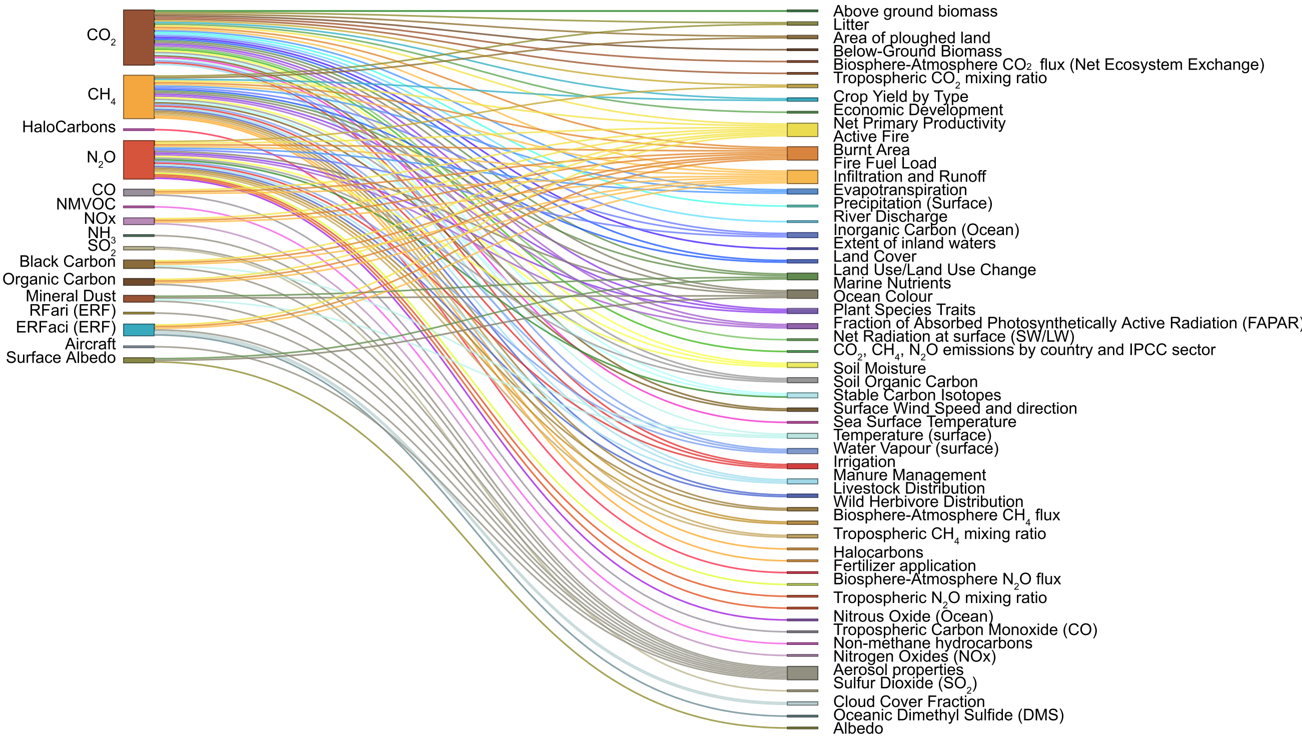

Fig. 2 On the left, climate forcing components as defined in the IPCC Fifth Assessment Report (Myhre et al. 2013) and on the right, the environmental variables found to be essential to quantify these components for the African continent

the same time, marine ecosystems are of high socio-economic importance for many African countries as coastal activities such as fisheries, tourism and commerce assure livelihood for large parts of the population. Therefore, a future climate forcing observing network across Africa needs to include both terrestrial and marine observational capacities.

The target variables for a continental observation system were derived through a combination of two approaches. In a top-down analysis, those variables which are required to quantify or estimate the major components of Africa-wide climate forcing were identified, based on the needs of Earth system research. Simultaneously, in a bottom-up approach, a list of relevant environmental variables was compiled by combining existing globally defined variable sets such as the essential climate, ocean and biodiversity variables, along with Africa-specific environmental and ancillary variables. The variables were prioritized based on a survey among 40 participants from the African and European environmental research community. The integration of findings from both approaches resulted in a set of 58 environmental variables (Fig. 2). The systematic and sufficient observations of these variables will increase the accuracy of African climate forcing estimates to global standards. The maximum acceptable uncertainties, and the observational requirements in terms of temporal and spatial resolution, were further defined for each variable (Beck et al. 2019).

As highlighted by Franz et al. (2018) and Smith et al. (2019), methodological protocols are the backbone of a harmonised RI. They allow for the comparison of observations and data products acquired from different sites, by different systems, in various countries and at different times. Protocols allow their integration with satellite products, and transparency and reproducibility over the whole measuring/monitoring, reporting and verification (MRV) process. Therefore, López-Ballesteros et al. (2020) identified 140 protocols developed by international research communities (e.g. ICOS, WMO, ICP Forests, FixO3) that are potentially applicable to the measurement of the essential variables identified. Based on the collated protocols and the feasibility assessment, a harmonised approach is proposed to enhance observational capacity in Africa, with the differentiation of at least two types of sites. ‘Basic’ sites collect environmental measurements using relatively cheap and simple methods, improving the spatial coverage in the main biomes, anthromes and land use types. Advanced ‘key sites’ which would collect a larger set of variables, measured at high temporal resolution, usually with sophisticated instruments requiring specialised training, allow for a better understanding of driving processes in representative systems across the continent. Overall, these results aim at supporting existing observations and the implementation of new observations in under-studied regions (to cover the whole

African continent including its coastal zone) by following minimum international interoperability principles. Additionally, all these methodological materials must support the capacity development programs envisaged to develop the human resources required for the long-term success of newly implemented environmental observations.

The necessity for an e-infrastructure

Based on the inventory assessment of available data, measurements and capacity, the necessity for an appropriate e-infrastructure became obvious. In order to generate synergies with existing activities, an e-infrastructure that has been built by the South African Environmental Observation Network (SAEON) was taken as a starting point and linked to the SEACRIFOG Collaborative Inventory Tool[3] that can be used to visualise information on essential variables, data products, observation infrastructures and measurement protocols in Africa (Beck et al. 2019). The structure is open for advancements and adjustments in the future. Therefore, the 'blueprint' e-infrastructure should only be seen as a brokering registry for all available data products related to environmental monitoring in Africa and can be extended to serve, for example the needs of a future African Research Infrastructures that encompass and go beyond measuring carbon and GHG emissions.

A roadmap describing the status and anticipated technical readiness level which allows to move from a simple to a more advanced solution was developed. The e-infrastructure was designed to serve the African RI, including both operational data handling of the measurement infrastructure and services provided for scientific data evaluation and modelling. The costs of such an endeavour are small compared to investments and operational costs of measurement stations with an e-infrastructure that is thoroughly designed and implemented playing an essential role in the operation of the measurement infrastructure.

Capacity development

In parallel to mapping of needs for a continental observational research infrastructure, the SEACRIFOG project engaged key stakeholder groups to identify capacity development needs in the context of developing, maintaining and operating suchlike. It concluded that in addition to technical and financial investments (outlined in subsequent sections), a functional RI requires the development of both human and technical capacities, in terms of skilled scientific and technical personnel as well as state-of-the-art data centres, calibration laboratories, and efficient local instrument support. The scarcity of capacity across most parts of Africa constitutes the major obstacle towards the establishment and operation of a continentally owned and coordinated RI (Atickem et al. 2019) and related research. For each highly specialised scientific and technical subdiscipline identified, it is currently hard to find the necessary human resources in Africa, and hard to retain them in the financially uncompetitive field of environmental observations (OECD 2009). Moreover, there are currently no continental policies and supporting agreements in place to guide African states in developing a joint continental observational strategy and to regulate data exchange, data hosting and tax-free movement of equipment. Thus, any research infrastructure that is likely going to be established in Africa calls for long-term capacity development programs which are coordinated across the continent. Such programs have to include capacity development at scientific level (e.g. research institutions, universities), technical level (e.g. research institutions, specialised SMEs, national authorities) and administrative level (local and national authorities). One example for a multilateral capacity development program is the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) which has established 12 graduate schools with the aim to train the next generation of scientists and potential decision-makers (www.wascal.org). Several other examples exist, even though those programmes are commonly not linked. In addition to financial and technology transfers, such capacity development programmes constitute an opportunity for industrialized regions to support locally driven capacity development in direct accordance with Article 11 of the Paris Agreement. As a co-benefit, the economic development of the continent will be favoured.

Regional to local-scale example

While it has become apparent that any additional observational platform will assist in further reducing the uncertainty in the climate forcing of and around the African continent, it needs to be stated that some information may be more important than other. For instance, monitoring the coastal zone with its local fisheries is vital with regards to human health, nutrition and economy. Furthermore, accurate estimates of the environmental footprint of agricultural and particularly livestock systems is key to better constrain emissions and to develop climate-smart agricultural mitigation and adaptation strategies (Clute 1982; Abdulai and Hazell 1996; Thornton and Herrero 2010; Bryan et al. 2013). An example of what can be achieved with focused and continuous in situ observations has been shown by the Mazingira Centre—a state-of-the-art environmental research centre—hosted by the International

[3] https://seacrifog.saeon.ac.za/.

Livestock Research Institute (ILRI) in Nairobi, Kenya. The Centre established the first Tier 2 GHG emissions assessment of a variety of land use types including smallholder farmlands, croplands, savannas, conservation areas as well as forests (Pelster et al. 2017; Wanyama et al. 2018; Wachiye et al. 2019); dominant livestock systems (Ndung'u et al. 2019); and their individual system components (Pelster et al. 2016; Goopy et al. 2018; Zhu et al. 2018, 2020). This specific work (i) has led first of all to better scientific understanding of the environmental footprints of agroecosystems in sub-Saharan Africa (SSA), accounting for the sometimes unique settings of African livestock systems, (ii) supporting governments in East Africa to fulfil their NDC requirements and accurate GHG emissions reporting to UNFCCC while (iii) identifying and testing potential GHG mitigation measures in parallel (Herrero et al. 2016; Ali et al. 2019; Onyango et al. 2019; Goopy et al. 2020). The centre has further investigated the existing uncertainties, knowns and unknowns in nutrient budgets from key ecosystems and landscapes, such as semi-arid drylands and savannah ecosystems (Carbonell et al. 2021), and was thus able to identify hotspots of nitrous oxide emissions from cattle enclosures which are of continental and global importance (Butterbach-Bahl et al. 2020). Other recent work has also revealed how severe undernutrition in cattle increases their enteric methane production (Goopy et al. 2020). In the next steps, and given the necessity of intensifying agricultural production of major staple crops such as maize, a projection of nitrous oxide emissions when closing maize yield gaps by 2050 was performed based on available publications that measured both crop yields and GHG emissions (Leitner et al. 2020). With such focused approaches of bringing a wide variety of expertise and observations together, the actual services for stakeholders ranging from line ministry staff, academia as well as farmers become a reality.

Which observations should be made where, and what are the costs?

An Africa GHG observation system, as proposed, can inform climate change mitigation, adaptation and economic development decisions. Africa, whose agriculture and food security is vulnerable to global warming, changing precipitation patterns—including droughts and floods—and climate-linked effects such as the locust invasion in East Africa in 2020 (Kimathi et al. 2020), need data, human and institutional capacity development and systemic governance for mitigation and adaptation (Dobardzic et al. 2019). The benefits for society of a comprehensive environmental observation system spanning the African continent would outweigh the investments of building and maintaining it.

Unintended redundancy that does not serve interoperability or robustness and could lead to economies of scale (Table 1) should be avoided. Thus, the SEACRIFOG consortium ran optimization algorithms coupled to top-down inversion techniques to identify the best locations for new observations, such that they reduced the uncertainty in the GHG budget of Africa by the greatest amount (Fig. 3, Nickless et al. 2020). In order to minimise the costs, various technologies that meet the required standards were considered for each of the essential variables (López-Ballesteros et al. 2018, 2020; Beck et al. 2019).

The network design for in situ atmospheric monitoring sites in Africa is an example of how to plan an effective observational network at minimum cost. The study considered many potential locations in Africa and identified in an inverse modelling approach those that reduced uncertainty of African GHG budgets most. The design approach placed stations into the network sequentially, so that the solution provided a ranking of stations to be considered for establishment or refurbishment based on the percentage uncertainty reduction in the total African GHG budget that could be achieved (Fig. 3). The analysis considered each of the three major GHGs separately and provided a solution which optimised across all three gases. The largest amount of uncertainty in the total African GHG budget was due to biogenic GHG emissions, and therefore sites were located near the regions of greatest biogenic activity (Nickless et al. 2020), predominantly tropical rainforest, subtropical and tropical dry forest and grass savanna biomes. The regions/countries which were most frequently included in the network design under various configurations included Angola, the Congo basin and Botswana. For the implementation of the network, the cost of the site versus its ranking in the network solution should be considered. The resulting network would be able to achieve an uncertainty reduction in the total African GHG budget for CO_2 of up to 55%, and lower levels for CH_4 and N_2O. This emphasizes the need for an integrated network to reach higher levels of uncertainty reduction. It would include atmospheric measurements sites, such as proposed in the network design study by Nickless et al. (2020), as well as satellite observations, and ecosystem measurements of GHG fluxes which can improve models predicting biogenic GHG fluxes in African ecosystems. Furthermore, it is important to note that some of the tropical African stations that were used in the study are already active. It would therefore probably cost less to upgrade them than it would cost to build a new site in a hard-to-reach location with no prior observational experience.

Table 1 Levelized annuals costs as well as total costs for the relevant infrastructure components over 30 years (in alphabetical order). The individual components are as follows: **Atmospheric measurements** are based on a continental network of tall towers and mountain stations for GHG concentration data collection in the atmosphere; **Automated weather stations** are necessary since meteorological and hydrological models as well as GHG estimation models in agriculture and forestry depend on a dense network of weather stations; **Ecosystem measurements** comprise are direct observations of sources and sinks of GHG fluxes between land surfaces and the atmosphere; **Measurements campaigns** primarily focuse on three essential variables for more reliable models to be constructed: species traits, crop yields and land use; **Modelled products** are observation products from processes and phenomena pertaining to the atmosphere that incorporate computations and focus on weather predictions; **National inventories** are considered as a necessity to sustain the responsible institutions to enable capacity for the submission of GHG inventories by African governments under the United Nations Framework Convention on Climate Change (UNFCCC); **Ocean observations** include basic GHG and other observations within eight ecological/biogeochemical provinces surrounding the African continent (Longhurst et al. 1995); **Remote sensing products** are data generated by satellites and other technologies such as drones and cameras; and **TCCON stations** that use sunlight which is directed into a spectrometer to measure the absorption of sunlight by atmospheric GHG and other trace gases

GHG observation system component	Initial cost	Operational cost	Data processing costs	Full-time equivalent (FTE)	Depreciation cost	Levelised cost	Percentage
	M€	M€ yr-1	M€ yr-1	M€ yr-1	M€ yr-1	M€ yr-1	%
Atmospheric measurements	5.50	0.80	0.11	0.33	0.92	2.34	13%
Automated weather stations	2.70	0.60	0.40	0.15	0.45	1.69	9%
Ecosystem meaurements	6.35	0.50	0.20	0.63	1.06	2.60	14%
Measurement campaigns	0.00	0.45	0.00	0.00	0.00	0.45	2%
Modelled products	0.15	0.00	1.43	3.15	0.03	4.61	25%
National inventories	0.00	0.05	0.00	0.00	0.00	0.05	0%
Ocean observations	1.96	0.67	0.01	0.1	0.33	1.18	7%
Remote sensing products	0.15	0.00	1.43	3.15	0.03	4.61	25%
TCCON sites	0.60	0.20	0.10	0.15	0.10	0.57	3%
Total (per year)	**15.45**	**2.60**	**3.66**	**7.56**	**2.90**	**18.09**	**100%**
Total (30 years)						**542.76**	

Stakeholder involvement and aspects of implementation

Designing GHG observations under a changing climate in Africa, while addressing the double challenge of climate change adaptation and mitigation, is a huge effort that implies the integration of different disciplines and the support of a strong policy mandate with substantial investments. The final question is how to achieve these investments in an African GHG observation system and to ensure the desired impact. It is clear that the implementation needs a strong and sustainable institutional framework that includes national governments and scientific institutions taking ownership of the observational system, its e-infrastructure and the related research and beyond those multi-national institutions including the African Union and the World Meteorological Organization (WMO).

Stakeholder involvement which has become a common practice in interdisciplinary research projects (Mielke et al. 2017; Ginige et al. 2018) has been applied in SEACRIFOG to ensure that local African knowledge is mainstreamed into the project design (López-Ballesteros et al. 2018). A wide range of actors belonging to different sectors have been consulted to ensure that the design and the strategic plan for implementation of the observational network meet the users' needs. Within SEACRIFOG, the stakeholders' engagement was obtained through the organisation of three workshops, each in a different African region (Eastern, Western and Southern Africa) and through the establishment of the SEACRIFOG Dialogue Platform.

A GHG observation system, as well as the derived information, proved to be important for a range of African stakeholders, including farmers, fishermen, environmental managers, research institutions, governmental and non-governmental organisations, regional bodies and UN agencies. Monitoring GHG budgets allows key stakeholders to address climate change mitigation and adaptation measures through informed environmental planning and management. From the stakeholder analysis, the current knowledge on these topics is largely hindered by limited data/metadata availability, accessibility, usability, interoperability, resolution, format and quality. The solution for Africa is unlikely to simply be a system transposed from developed country approaches for RIs. These are not directly applicable to the African context for reasons such as (1) high costs for implementation and maintenance, (2) scarcity of qualified personnel and specialised companies, (3) problems with unreliable energy supply, (4) accessibility and protection of field sites and (5) challenging climatic conditions (López-Ballesteros et al. 2018). Technological and infrastructural gaps can be filled through

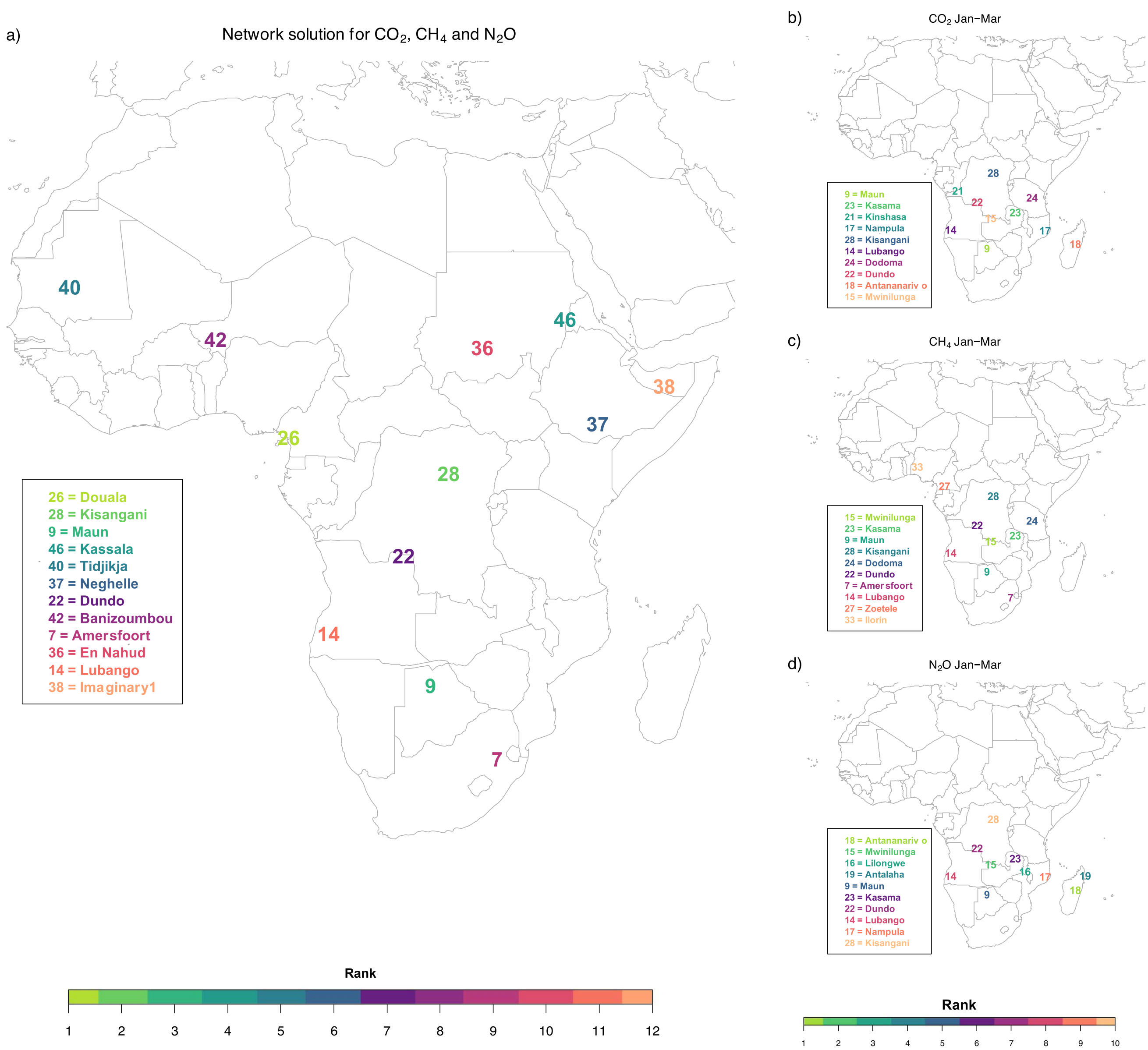

Fig. 3 **a** Optimal locations to situate twelve new atmospheric monitoring sites to an existing network in order to reduce the overall uncertainty of CO_2, CH_4, and N_2O fluxes from terrestrial Africa. The year 2012 has been taken as a representative year, optimized over all three gases simultaneously. Sites are added sequentially and are colored according to the rank in the optimal design, with light-green sites representing the site with the largest uncertainty reduction and which is the first site added to the network. Figure panels **b**, **c**, and **d**: optimal locations to situate new atmospheric monitoring sites to a network of ten sites to reduce the overall uncertainty of CO_2 (**a**), CH_4 (**b**), N_2O (**c**) fluxes from terrestrial Africa for the period January to March. Sites are colored according to the rank in the optimal design, with light-green sites representing the site with the largest uncertainty reduction and which is the first site added to the network

international cooperation coupled with a suitable strategy for promoting public and private investments, including for example the Green Climate Fund (GCF), World Bank (WB) and African Union (AU) (Afful-Koomson 2015).

Similarly, methodological guidance and an increasing exploitation of research results can be achieved through a collaborative and interactive network among the relevant parties, promoting best practices and capacity development. Besides research and technology, a comprehensive approach must consider not only scientific and ecological issues but also socio-economic dynamics (e.g. land tenure, urbanization, job opportunities, markets, prices, investments). Any planning strategy for an environmental RI with distributed field sites needs to build on what already exists and rely on an optimal network design process based on objective scientific analyses (Sulkava et al. 2011; Lucas et al. 2015; Ziehn et al. 2016). Strengthening cooperation between Africa and Europe on the topics of GHG observations, land use change and food security needs to consider these aspects as part of the same common interest in achieving global objectives and moving from being part of the climate change problem to be a proactive part of the solution.

It is recommended that neo-institutional economic and political frameworks (e.g. Ostrom's institutional analysis framework as used by Nigussie et al. (2018)) be applied for the diagnosis and analysis of impact. The related theory of change proposes monitoring of research activities through impact pathways. Such strong research component may result in a 550 M€ investment over 30 years which has to be justified by a commensurate return on investment with regards to accuracy, standardisation, reliability of data transmission and archiving, adequate coverage and precision of the observational elements as well as high societal impact of the knowledge produced by the researchers.

Conclusion

The SEACRIFOG consortium has developed a blueprint for an African environmental research infrastructure that could provide the foundation for establishing standardised environmental observations across the continent. This is a necessary step towards achieving national, regional and global objectives with respect to development within the constraints of a worldwide climate crisis. The blueprint is feasible and would represent a substantial advance over the current situation.

Although building on existing infrastructure, considerable investment is needed to lift the existing observations to the desired coverage and enable African scientists to generate the knowledge their societies need to mitigate and adapt to climate change. Pathways towards intended goals need to be reflected on in long-term perspectives for meeting sustainable development goals. Strategies for knowledge management and dialogue between actors at sub-national, national, regional, continental and international level should be inclusively instituted during implementation as the RI works towards societal relevance.

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